STUDY OF A SMALL SYNCHROTRON RADIATION SOURCE FOR RADIOMETRY *

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Abstract

The conceptual design of a low energy electron storage ring for radiometric applications, based on a detailed design study [1], is presented. Radiometric tasks demand for a tunable electron energy in the range from $200\,$MeV to $600\,$MeV to provide tunable, quasi monochromatic undulator radiation in the spectral range from the IR to the VUV and bending magnet radiation with adjustable characteristic energy. The achievable lifetime of a $100\,$mA stored electron beam should be not less than $1\,$h. The ring is supposed to be located at the BESSY II site in Berlin-Adlershof, close to the BESSY II booster synchrotron, which can be used as a full energy injector. A compact racetrack lattice of $34.2\,$m circumference is suggested, composed of two triple bend achromats and two straight sections of $5.6\,$m, one of it for the use of insertion devices. Beam optical parameters such as linear and nonlinear properties of the lattice are presented. Requirements for the rf and vacuum system, resulting from lifetime design goals, are defined. Expected synchrotron radiation spectra from dipoles and insertion devices are presented.

1 INTRODUCTION

One of the numerous applications of the electron storage ring BESSY I in Berlin was radiometry - the metrology with photons. Since 1984 the storage ring was used as a primary radiation standard in the UV/VUV [2] for calibration issues. This primary standard was lost with the shut down of BESSY I at the end of 1999. In the beginning of that year BESSY II, a high brilliance, third generation synchrotron radiation light source, started its regular user operation. With BESSY II the spectral range for radiometric applications can be expanded to the hard X-ray region. As a result of the high electron energy and thus the hard spectrum of dipole and wiggler radiation BESSY II is not so well suited for radiometric application in the UV/VUV. Additionally, undulator radiation in the VUV spectral range of a few $10\,$eV, generated with the normally used insertion devices, can not be provided.
A compact low energy electron storage ring could cover this range from the IR to UV/VUV. In a collaboration between BESSY and *Physikalisch-Technische Bundesanstalt* (PTB), guidelines for the storage ring design were formulated:

- small size of storage ring
- electrons are to be stored and ramped in the energy range from $200\,$MeV to $600\,$MeV, to produce intense dipole and insertion device radiation in the UV/VUV spectral range,
- low emittance to achieve high brilliance synchrotron radiation,
- beam lifetimes of more than $1\,$h at an average ring current of $100\,$mA in the whole electron energy range.

2 OPTICAL LATTICE

The design of the storage ring is based on a racetrack shaped lattice with two TBA (Triple Bend Achromat) arcs, connected by dispersion free tuned straight sections. One of the two straight sections offers space for a $5.6\,$m long insertion device. The other one is occupied by the injection magnets and the rf cavity.
In Table 1 the main optical lattice parameters are listed. Figure 1 shows the beta functions and the dispersion of one unit cell. The six main bendings are rectangular, 60° magnets, producing field strengths up to $B \approx 1.55\,$T (for $E = 600\,$MeV) with high homogeneity and moderate saturation. With two quadrupole magnets per achromat the

lattice type	TBA-racetrack
electron energy E / MeV	200 to 600
circumference C / m	34.2
bending radius ρ / m	1.289
natural emittance ε / nrad m	30^*
working point Q_x/Q_y	$2.86/1.20$
maximum beta function $\hat{\beta}_x/\hat{\beta}_y$ / m	$20.0/7.6$
maximum dispersion $\hat{\eta}_x$ / m	1.10
natural chromaticity ξ_x/Q_x / ξ_y/Q_y	$-1.95/-3.52$
damping partition function J_x	1.10
momentum compaction factor α	0.0474
natural energy width σ_E / %	0.031^*
critical photon energy ε_c / eV	111^*
damping times $\tau_x/\tau_y/\tau_s$ / ms	$47/52/27^*$
energy loss per turn U_0 / eV	1758^*

Table 1: Main optical lattice parameters, * energy dependent parameters at $E = 400\,$MeV

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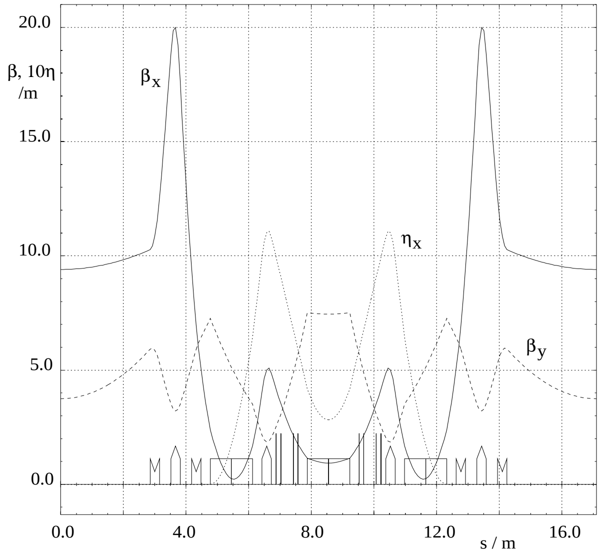

Figure 1: Beta functions and dispersion of a unit cell

dispersion outside the achromat can be tuned to zero. Four quadrupole triplets at the beginning and end of each straight section allow an easy adjustment of beta functions and working point. Four sextupole magnets per achromat are arranged in two families to correct the chromaticity.

The natural emittance ε of the designed lattice is close to its theoretical minimum. Assuming that the minimum emittance of a TBA-structure is about that of a DBA-structure with equal number of dipole magnets [3], $\varepsilon_{TBA} \approx \varepsilon_{DBA} = C_q\,\gamma^2\,\Theta^3/(J_x\,4\sqrt{15})$ we get $\varepsilon/\varepsilon_{TBA} \approx 1.6$, a value which is smaller than that of most other TBA storage rings (C_q: quantum excitation constant, Θ: dipole bending angle) . One key for reaching such a small emittance might be the quadrupole triplets in the straight sections. They make possible an effective emittance optimisation via tuning the horizontal beta function inside the dipole magnets and the phase advances inside the achromat. For horizontal phase advances between $180° - 260°$ the emittance of a TBA structure reaches a broad minimum [3]. While many comparable TBA lattices have a phase advance between $130° - 150°$ the presented lattice has $167°$ phase advance and is thus near the optimal range. Nonlinear optical limitations, often occuring in lattices nearly tuned to their minimum emittance, where not observed. Both, linear and nonlinear ring properties are good: the momentum acceptance of the chromatic corrected magnet optics is greater than $\pm 3\%$. Tune shifts with amplitude are small and the dynamic aperture with small field and alignment errors exceeds the mechanical, vacuum chamber aperture at least by a factor of two. The studied insertion devices (see section 4) could be matched to the optics: while at high energies this is without any problem, at low energies larger changes of the vertical beta function at a fixed working point are unavoidable. The enlarged maximum value leads in turn to a reduced vertical betatron acceptance. In addition, the dynamic aperture with an insertion device is still larger than the mechanical one.

3 BEAM LIFETIME

The significant beam lifetime limitations for the designed storage ring are residual gas and Touschek lifetime. Both are strongly influenced by the parameters of the rf and vacuum system. Table 2 contains the parameters, relevant for lifetime considerations. The choice of rf frequency to-

rf frequency f_{rf} / MHz	500
rf voltage V_{rf} / kV	500
vacuum chamber diameter $d_x \times d_y$ / mm	65×35
residual gas base pressure p / mbar	$1.0{\cdot}10^{-9}$
gap in bunch train filling	$\approx 20\%$
eff. broadband impedance $\lvert Z/n\rvert^{\parallel}_{eff}$ / Ω	2.0

Table 2: Assumed values of rf and vacuum system parameters for lifetime calculations

gether with the cavity voltage determines the rf momentum acceptance and influences bunch volume and current and thus the Touschek lifetime. Vacuum chamber and pumping scheme layout determine the residual gas pressure and composition, transverse betatron and momentum acceptance and thus both gas and Touschek lifetime.

The residual gas lifetime is mainly determined by scattering events with atomic nuclei: elastic (Coulomb) and inelastic (Bremsstrahlung) scattering, whereby here the Coulomb lifetime τ_c dominates. It is proportional to the limiting transverse betatron acceptance $\mathcal{A} = |d_u^2/(4\beta_u)|_{min}$ ($u = x$ or y) and to the inverse of the mean beta function: $\tau_c \sim \mathcal{A}/ < \beta_u >$. To achieve a long Coulomb lifetime beta functions, especially that of the limiting vertical plane, have been tuned to low values. Simulations of the pressure distribution have been performed, considering thermal and synchrotron radiation induced gas desorption. The simulations show, that a base pressure of $1.0{\cdot}10^{-9}$mbar and an energy depending working pressure of $p \leq 1.7{\cdot}10^{-9}$mbar for currents $I \leq 100$mA can be reached. The corresponding residual gas lifetime ranges from 4.2 h at 200 MeV to 20 h at 600 MeV in the zero current limit and 4.1 h at 200 MeV to about 13 h at 600 MeV with an average ring current of 100 mA.

At the design current of 100 mA the Touschek lifetime τ_T is the main limitation of the beam lifetime. It depends sensitively on momentum acceptance $\mathcal{A}_p$, bunch density n and electron energy E: $\tau_T \sim n\,E^2\,\mathcal{A}_p^3$. The momentum acceptance of the machine can be limited by rf acceptance or the transversal acceptance, given by the dynamic aperture of momentum deviating electrons or by the horizontal aperture. In our case the dynamic aperture of electrons with momentum deviations of $\pm 3\%$ is still larger than the horizontal chamber aperture. Thus the transverse acceptance is determined by the horizontal aperture in dispersive sections and amounts to 1.5% for Touschek events inside the achromat and to 3.0% for those in non-dispersive ring sections. The rf acceptance goes from 2.4% at 200 MeV down to 1.4% at 600 MeV. Bunch current and bunch volume respectively emittance and bunch length depend strongly on the parameters of the optical lattice and the rf system. With the chosen rf parameters the zero current bunch length ranges from 1.2 mm at 200 MeV to 6.4 mm at 600 MeV. Current dependent effects, mainly "Intra Beam Scattering" and "Turbulent Bunch Lengthening", lead to an enlargement of the bunch volume. At high energies the bunch volume stays nearly constant, while it grows drastically at low energies. As a consequence above a few mA ring current already the shortest Touschek lifetime occurs not at the lowest energy of 200 MeV but at slightly higher energies. Results of calculations with ZAP [4] show at the design current of 100 mA a broad minimum of the Touschek lifetime of about 1.4 h at 270 MeV. It rises to 1.7 h at 200 MeV and 13 h at 600 MeV.

In Figure 2 the residual gas, Touschek and total lifetime with 100 mA average ring current are presented as function of the electron energy. The total beam lifetime shows a broad minimum of 1.2 h between 200 MeV and 300 MeV and rises to 6.5 h at the maximum energy of 600 MeV.

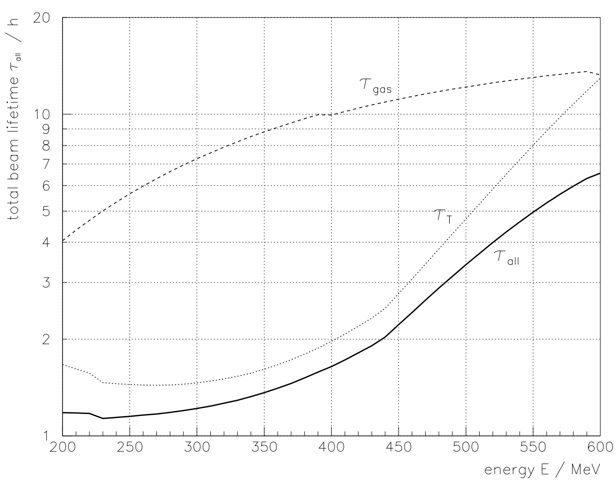

Figure 2: Total beam lifetime (full line), Touschek lifetime (dotted line) and residual gas lifetime (dashed line) vs. electron energy at $I = 100$ mA

4 SYNCHROTRON RADIATION SPECTRA

Figure 3 shows the spectral brilliance of the radiation from a dipole magnet and two typical insertion devices, taking defraction limits into account. The maximum brilliance of the dipole magnet radiation occurs at about 300 eV and yields $6.0 \cdot 10^{12}$photons$/($s 0.1%BW mm^2 mrad$^2)$ with

	U180 [5]	U49 [6]	
type	el. magn.	hybrid	
period length / mm	180	49	
number of periods	21	84	
min. gap height / mm	32	20	32
max. magnet field / T	0.460	0.546	0.268

Table 3: Insertion device parameter: U180 and U49

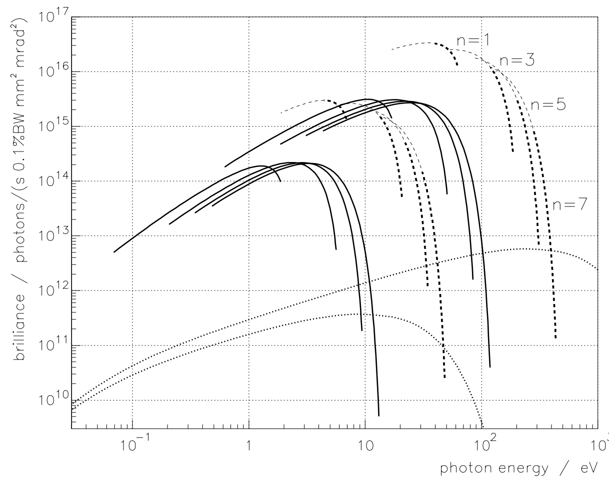

Figure 3: Spectral brilliance with $I = 100$ mA at minimum ($E = 200$ MeV) and maximum energy ($E = 600$ MeV): full line: U180; dashed line: U49 (thick: $g = 32$ mm / thin: $g = 20$ mm); dotted line: dipole magnet

100 mA beam current.

Main parameters of the two studied insertion devices are presented in Table 3. While for beam currents of 100 mA the maximum brilliance of the U49 occurs at 40 eV and is $4.0 \cdot 10^{16}$photons$/($s 0.1%BWmm^2 mrad$^2)$, the U180 brilliance takes its maximum of $4.0 \cdot 10^{15}$photons$/($s 0.1%BW mm^2 mrad$^2)$ at photon energies of about 20 eV.

5 CONCLUSION

The storage ring design of a synchrotron radiation source, optimised for radiometric applications, is presented. The calculated radiation spectra reach their maxima in flux and brilliance in the UV/VUV, the desired spectral range. With good linear and nonlinear properties the natural emittance of the lattice reaches nearly the expected minimum value of a 2fold TBA-structure. The estimated lifetimes of more then one hour at a current of 100 mA and all energies fulfil the formulated conditions. All machine properties make the presented storage ring not only a well optimised tool for radiometry but in general a suitable synchrotron radiation source for research in the spectral range from the near IR to the VUV.

REFERENCES

[1] M. Abo-Bakr, PhD thesis, Humboldt-Universität zu Berlin, 2000, e-mail: abobakr@bessy.de

[2] F. Riehle, B. Wende, Optical Letters,**10**, 1985, p.365-367

[3] G. Wüstefeld, BESSY TB 108/87, Berlin, 1987

[4] M.S. Zisman, S. Chattopadhyay, J.J. Bisognano, LBL-21270, 1986

[5] R. Klein, J. Bahrdt, D. Herzog, G.Ulm, Journal of Synchrotron Radiation, **5**, 1998, p.451-452

[6] J. Bahrdt, BESSY, http://oracle.bessy.de/... .../para_list/pl_0_left.html, 2000